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Performance of the Volumetric Diffusive Respirator at Altitude

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Aeromedical transport of ventilated patients requires continued performance of equipment at altitude. Changes in barometric pressure with increasing altitude are associated with alterations in gas density, which can affect ventilator performance. The volumetric diffusive respirator is a pneumatic ventilator used by the U.S. Army Burn Team and the U.S. Air Force Lung Team for patients with hypoxemic respiratory failure. The volumetric diffusive respirator was tested in a man-rated altitude chamber at sea level, 8,000, and 16,000 feet corresponding to barometric pressures of 760, 564, and 412 mmHg. Airway pressures, flow, and volume were continuously measured with a pneumotachograph and differential pressure transducer during ventilation of a test lung. Data were recorded for later analysis. Mean measured values at each altitude were compared to sea level data using analysis of variance. At each increase in altitude, positive end expiratory pressure and peak inspiratory pressure were increased by 30-40%. Tidal volume remained within 15% of sea level values. Respiratory rate fell, while inspiratory time increased and high frequency pulse rate fell. At altitude, positive end expiratory pressure and peak inspiratory pressure increase while pulse frequency diminishes. These increases can result in high airway pressures and should be corrected to prevent untoward events.

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Ventilator, aeromedical transport, high frequency ventilation, ventilator induced lung injury

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1.0 SUMMARY

Aeromedical transport of ventilated patients requires continued performance of equipment at altitude. Changes in barometric pressure with increasing altitude are associated with alterations in gas density, which can affect ventilator performance. The volumetric diffusive respirator is a pneumatic ventilator used by the U.S. Army Burn Team and the U.S. Air Force Lung Team for patients with hypoxemic respiratory failure. The volumetric diffusive respirator was tested in a man-rated altitude chamber at sea level, 8,000, and 16,000 feet corresponding to barometric pressures of 760, 564, and 412 mmHg. Airway pressures, flow, and volume were continuously measured with a pneumotachograph and differential pressure transducer during ventilation of a test lung. Data were recorded for later analysis. Mean measured values at each altitude were compared to sea level data using analysis of variance. At each increase in altitude, positive end expiratory pressure and peak inspiratory pressure were increased by 30-40%. Tidal volume remained within 15% of sea level values. Respiratory rate fell, while inspiratory time increased and high frequency pulse rate fell. At altitude, positive end expiratory pressure and peak inspiratory pressure increase while pulse frequency diminishes. These increases can result in high airway pressures and should be corrected to prevent untoward events.

2.0 INTRODUCTION

Aeromedical transport of critically ill patients requires continued, accurate performance of equipment regardless of changes in altitude. Changes in barometric pressure with increasing altitude are associated with alterations in gas temperature, density, and humidity. These changes can affect the performance of mechanical ventilators calibrated for operation at sea level. Effects of increasing altitude include changes in the movement of gas through fixed orifices altering accuracy in ventilator settings as well as the measurement of flow and volume (1-4).

During the last decade of conflict in the Middle East, the long-range transport of critically ill patients with respiratory failure has become routine (5,6). Both the U.S. Air Force Acute Lung Team and the U.S. Army Burn Team have described the use of non-traditional ventilators and extracorporeal membrane oxygenation for the most critically ill patients (6). Barillo and colleagues have described the use of the pneumatically powered and pneumatically controlled VDR-4 [volumetric diffusive respirator] (Percussionaire, Sandpoint, ID) in the movement of 33 burn casualties between the theater of operations and San Antonio, TX (7). This retrospective review did not address any issues related to device performance.

The impact of altitude on ventilator performance is exacerbated in devices relying on pneumatic control (8). A review of the literature failed to demonstrate any formal evaluation of the impact of changes in barometric pressure on performance of the VDR-4 at altitude.

3.0 METHODS

3.1 Device Description

The VDR-4 is a pneumatically powered and pneumatically controlled device commonly classified as a high frequency percussive ventilator (9). The breath delivery allows a set pressure, positive end-expiratory pressure (PEEP)/continuous positive airway pressure (CPAP), percussive frequency, and inspiratory and expiratory time. The breath delivery is accomplished through a

spring loaded, sliding venturi (Phasitron®) connected to the endotracheal tube. The action of the venturi is to deliver a series of high frequency pulses from the ventilator, building to a plateau pressure. The positive pressure delivery of each percussive pulse is followed by a passive fall in pressure as the spring moves the venturi back in to an expiratory position. Because the volume delivered under pressure is greater than the passive expiratory phase, this creates the characteristic stair-step increase in airway pressure (Figure 1). The control mechanisms of the VDR-4 include a combination of a needle valve and a normally open cartridge. The movement of gas to and from this control system relies on the movement of gas through known restrictions and changes in pressure on opposing sides of a diaphragm.

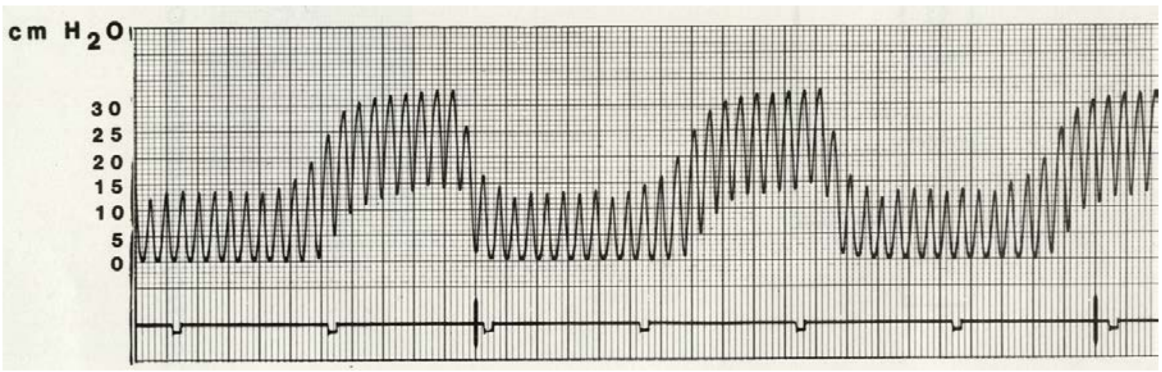

Figure 1. Stair-step increase in airway pressure.

Airway pressure is monitored by an integral aneroid pressure gauge, which is connected via standard tubing to the proximal airway (Figure 2). However, internally an orifice restrictor is placed in line to dampen the pressures in an attempt to display the estimated tracheal pressure. This requires the clinician to evaluate the pressure of an oscillating signal. For instance, the PEEP is read as the average pressure between the peak and trough movement of the manometer. A secondary measurement of pressure can be accomplished by using the Waveform Monitron (Percussionaire, Sandpoint, ID). This device uses a standard physiologic pressure transducer, which is not dampened by the restrictor and a display. This device chooses the highest pressure during the oscillation as the “PEEP.”

3.2 Protocol

The study was conducted at Wright-Patterson Air Force Base in a man-rated altitude chamber. We evaluated two different VDR-4 ventilators at sea level and altitudes of 8,000 and 16,000 feet (corresponding to barometric pressures of 760, 564 and 412 mmHg). Calibration of the ventilators required by the manufacturer was done prior to testing. An altitude of 8,000 feet was chosen to represent a simulated cabin altitude during Critical Care Air Transport Team flight. An altitude of 16,000 feet was chosen to represent the upper limit of crew functionality in the case of aircraft decompression. At sea level and each altitude, ventilators were connected to a two-chamber test lung (Training Test Lung, Michigan Instruments, Grand Rapids, MI) via the manufacturer-supplied circuit. A pneumotachograph was connected between the ventilator circuit and the test lung and the pressure measured by a differential pressure transducer. The signals for airway pressure, flow, and volume were collected on a breath-to-breath basis and recorded to a computer for later analysis. The system previously described by Allan was used

(10). After a 1-minute stabilization period, a minimum of 2 minutes of continuous data were collected at each combination of lung model and ventilator settings. At each altitude, the measurement system was calibrated using a 3-liter super syringe.

Figure 2. Aneroid pressure gauge.

We chose to use a single set of ventilator parameters based on values reported in the literature and changed the compliance and resistance settings to represent a patient with acute respiratory distress syndrome with and without elevated airway resistance (Table 1). Data were compared using analysis of variance with significance set at $p < 0.05$.

Table 1. Ventilator Settings during the Evaluation

Peak Pressure (cm H_2O)	PEEP/CPAP (cm H_2O)	Pulsatile Frequency (cycles/min)	Inspiratory Time/Expiratory Time (s)	Respiratory Rate (breath/min)	Compliance (mL/cm H_2O) and Resistance (cm H_2O/L/s) of the Test Lung
30	10	400	3.0/1.5	13	30 and 5
30	10	400	3.0/1.5	13	20 and 20

4.0 RESULTS

The measured PEEP and peak inspiratory pressure (PIP) increased by 3 to 5 cm H_2O with each increase in altitude. Tidal volume remained within 20% of sea level values (Figures 3 and 4). The respiratory rate fell from 13 to 11 to 10 breaths per minute from sea level to 8,000 and 16,000 feet (Table 2). The pulsatile frequency fell significantly with each step change in altitude. Each of these changes was significant to a $p < 0.0001$. Inspiratory time also increased significantly across the altitude changes (3.0 seconds vs. 3.53±0.1 seconds vs. 4.23±0.2 seconds, $p<0.01$). Expiratory time only changed slightly from 1.5 seconds to 1.76 seconds at 8,000 feet and 1.86 seconds at 16,000 feet.

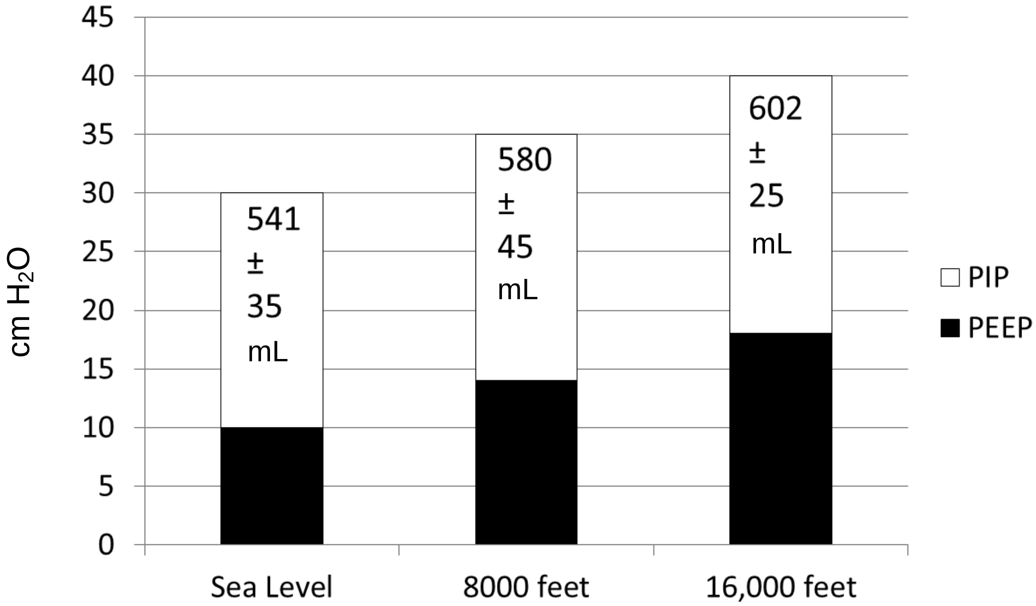

Figure 3. PEEP and PIP compliance of 30 mL/cm H_2O and resistance of 5 cm H_2O/L/s.

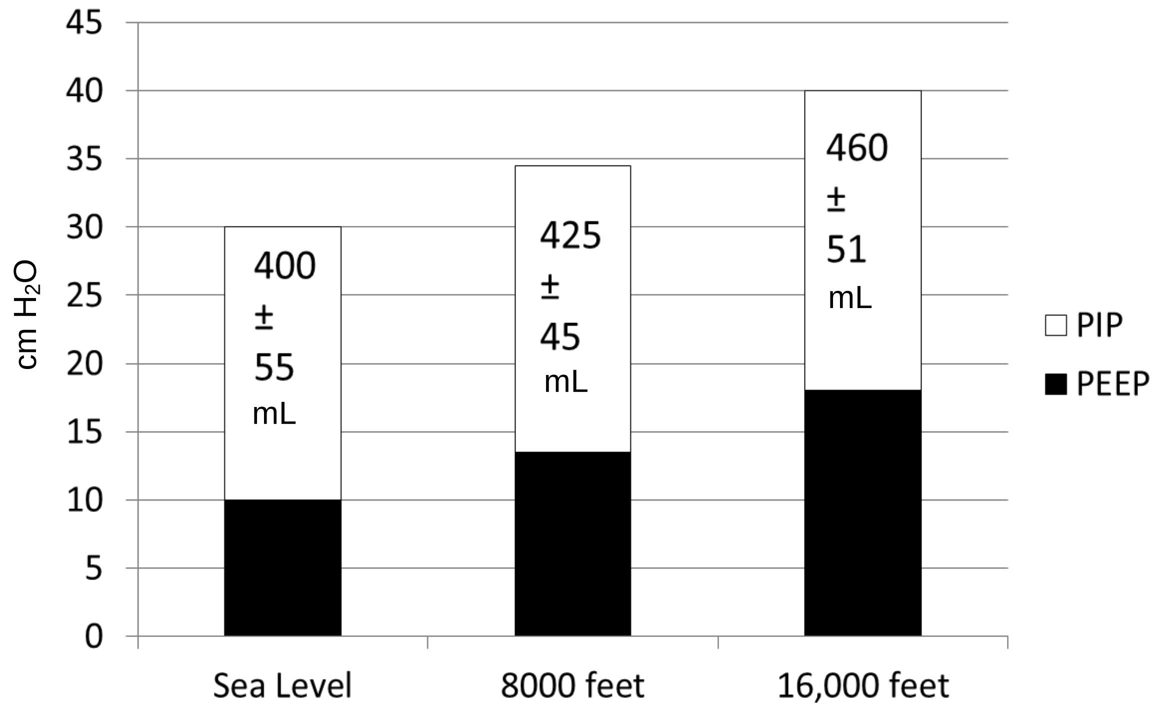

Figure 4. PEEP and PIP compliance of 20 mL/cm H_2O and resistance of 20 cm H_2O/L/s.

Table 2. Changes in Respiratory Rate, Pulse Frequency, and Inspiratory Time with Changes in Altitude

Setting	Sea Level	8,000 Feet	16,000 Feet
Respiratory Rate (breaths/min)	13	11	10
Pulsatile Frequency (cycles/min)	400 ± 11	345 ± 13	285 ± 14
Inspiratory Time (s)	3.0 ± 0.1	3.4 ± 0.01	4.0 ± 0.2

5.0 DISCUSSION

Ascent to altitude results in clinically relevant changes in the set parameters of the VDR-4 ventilator. Chief among these changes is a rise in both PIP and PEEP. Tidal volume (V_T) is only increased slightly. This finding may be due to the constant change in pressure (PIP-PEEP) and the fall in the percussive frequency. As percussive frequency falls, the volume of each percussive breath increases, resulting in a slight increase in V_T. During clinical use, a reduction in the pulsatile frequency is associated with a fall in arterial carbon dioxide ($PaCO_2$), suggesting improved ventilation.

Alterations in ventilator function at altitude have been well described (1-4). Electronic and microprocessor control of parameters such as rate and inspiratory time are not altered by hypobaric conditions. However, the performance of pneumatic- and fluidic-controlled devices is altered (4,8). In a given system, as gas density decreases, the volume through a given orifice increases. In ventilators such as the LTV-1000 that use a flow control valve and turbine, for a given inspiratory time a larger volume exits the flow control valve at altitude. The end result is an increase in V_T delivered that is inversely proportional to barometric pressure (1,2).

In an early investigation of the Bird Mark 8, Kirby et al. demonstrated that the pneumatic control of that device produced an increase in V_T and decrease in respiratory rate with altitude (8). The VDR is a pneumatic device that uses a series of needle valves and normally open cartridges to adjust pressure and time. For each control, as barometric pressure falls, the volume of gas delivered across a given time increases. Similarly, the time to increase pressure across a diaphragm in a normally open cartridge increases, resulting in a longer inspiratory time and slower rate. The CPAP setting of the VDR uses a pneumatic demand valve in concert with a needle valve. Not surprisingly, at a given setting, greater gas flow through the valve occurs at altitude. In our testing, this change in PEEP appears to be a percentage of set PEEP, so the greater the set PEEP, the greater the change at altitude.

The control settings on the VDR are based on alphanumeric controls (labeled 1-11), which preclude “dialing” in a given pressure. Additionally, changes in gas wall pressure can alter settings. This requires that the clinician set the pressure and PEEP by observing the movement of the analog manometer or the waveform screen. These methods alone can result in a significant disparity in desired settings. The analog manometer has a dampening system to allow a “mean” pressure displayed. However, it is not unusual for the manometer to oscillate ± 6 cm H_2O at the peak pressure, requiring each clinician to eyeball the setting. The waveform screen (Monitron) provides a numeric value for PIP and PEEP, but selects the highest pressure on the display. In our experiments, the difference between the researchers’ assessment of airway pressure on the manometer and the waveform screen was quite variable. This finding suggests that depending on the method with which pressure is measured, alterations at altitude may be more or less noticeable.

There is some clinical evidence to support these findings. In the paper by Barillo et al., significant changes in pH and $PaCO_2$ were seen between pre-flight and post-flight ventilation (7). The maximum pre-flight pH and $PaCO_2$ were 7.51 and 90.4 mmHg, and the maximum post-flight values were 7.61 and 56 mmHg. The minimum $PaCO_2$ pre-flight was 29 mmHg compared to a minimum post-flight $PaCO_2$ of 19 mmHg (8). These data include neither ventilator settings nor individual per patient changes. However, the data appear to suggest that minute ventilation has increased, although the mechanism is unclear.

Allan has also demonstrated increased V_T and minute ventilation with use of the VDR at high set airway pressures (10). These findings show the impact of the percussive breaths at the PIP on the total volume delivered (10). Cumulatively, these data argue for improved monitoring of VDR performance at altitude and ideally a method to determine delivered V_T. The to and fro gas movement makes this measurement difficult in the gas path, and methods that monitor chest expansion may be useful.

6.0 CONCLUSIONS

At altitude, the airway pressures delivered by the VDR are increased. These changes increase intrathoracic pressures and could adversely impact hemodynamics. The fall in percussive frequency increases minute ventilation. Methods are needed to more accurately and reproducibly monitor pressures and volume during use of the VDR, particularly during aeromedical transport.

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LIST OF ABBREVIATIONS AND ACRONYMS

CPAP	continuous positive airway pressure
$PaCO_2$	arterial carbon dioxide
PEEP	positive end-expiratory pressure
PIP	peak inspiratory pressure
V_T	tidal volume
VDR	volumetric diffusive respirator